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This report presents the findings made under the ARO contract listed. The significant results show how millimeter wave interconnects with embedded patterned substrate layers (EPSLs) improve insertion loss and coupling. The frequency domain S-parameter performance is characterized with a commercial full wave solver and effective permittivity is Additional results on how surface roughness in interconnects affect loss are shown. A simulation strategy that allows full three-dimensional statistical characterization of surface roughness was developed. This

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Final Report: Exploring New RF Circuit Structures with Embedded Patterned Substrate Layers

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This report presents the findings made under the ARO contract listed. The significant results show how millimeter wave interconnects with embedded patterned substrate layers (EPSLs) improve insertion loss and coupling. The frequency domain S-parameter performance is characterized with a commercial full wave solver and effective permittivity is Additional results on how surface roughness in interconnects affect loss are shown. A simulation strategy that allows full three-dimensional statistical characterization of surface roughness was developed. This methodology allows engineers to estimate the impact of the effects of surface roughness on signal propagation. EPSLs do improve insertion loss and reduces coupling in tightly spaced interconnects. The biggest improvement gains are for high permittivity substrates such as Alumina.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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22nd IEEE Conference on the Electrical Performance of Electronic Packaging. 27-OCT-13, . : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Arghya Sain	0.50	
Marcos Vargas	0.25	
FTE Equivalent:	**0.75**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Kathleen Melde	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

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Names of Personnel receiving masters degrees

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Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Abstract

This report presents the findings made under the ARO contract listed. The significant results show how millimeter wave interconnects with embedded patterned substrate layers (EPSLs) improve insertion loss and coupling. The frequency domain S-parameter performance is characterized with a commercial full wave solver and effective permittivity is Additional results on how surface roughness in interconnects affect loss are shown. A simulation strategy that allows full three-dimensional statistical characterization of surface roughness was developed. This methodology allows engineers to estimate the impact of the effects of surface roughness on signal propagation. EPSLs do improve insertion loss and reduces coupling in tightly spaced interconnects. The biggest improvement gains are for high permittivity substrates such as Alumina.

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I. Statement of the problem studied

Researchers have recently demonstrated transmission lines using metamaterials where signals can be guided and modified by including patterned layers of sub-wavelength periodic structures. The prior work typically involves periodic structures that apply to narrow frequency bands. Other research on dielectric packaging materials (using polymers) promise control over relative permittivity yet such materials are difficult to integrate as transmission line structures. Engineers are also realizing that as operating frequencies move upward towards millimeter wave frequencies, many of the physical artifacts that make up a printed circuit board material affect performance. This includes rough conductor surfaces which are generated in order to bond conductors onto dielectric materials.

The objective of this research is to develop new transmission lines with embedded patterned substrate layers (EPSL) that allow designers to control dispersion, impedance, and higher order modes in high data rate channels. An EPSL is a patterned layer with sub-wavelength structures that sits between the ground and signal layers in a RF transmission line. The outcomes of the project are to create modeling methods to accurately understand the impact of the EPSL on propagation. This allows the assessment of practical issues, such as conductor surface roughness, on interconnect performance.

II. Summary of the most important results

The most important outcomes of the project are:

1) The effects of the EPSL layers show a significant impact on interconnect performance above 30GHz. At lower frequencies, the added patterned layer is essentially transparent to the field in the transmission lines.
2) The work focused on thin dielectric materials. Our prior work showed that high density circuit packaging is trending toward very thin materials (thicknesses less than 10 mils.) Such materials allow multi-layer stack ups and may even be slightly flexible. Our prior work shows it is difficult to obtain transmission lines on thin materials that are have 50 ohm characteristic impedance, can be connected to probes for measurement, and achieve the layout design rules often specified by a fabrication vendor.
3) During the 6 month duration of the project, we found that the presence of the EPSL layer strongly depends upon the transmission line structure. While the transmission line characteristics for conductor-backed CPW (CB-CPW) are changed with the inclusion of the embedded-layer, more significant affects are apparent in coupled microstrip lines. This is due to the strong field penetration into the dielectric in microstrip compared to CB-CPW.
4) In a related study on conductor surface roughness for CPW structures, a full-wave modeling approach for characterizing conductor surface roughness was created. The method provides designers with a technique to characterize the effect of conductor surface roughness for different types of transmission lines. The approach allows for different types of substrates and different degrees of surface roughness. This approach can be used for the EPSL structures to study their performance in a

more practical fabrication environment.

The first part of the research investigated the effects of the EPSL with small disks on CB-CPW. The first results showed that the presence of the EPSL only had a slight effect on the propagation parameters. A series of parameter studies included varying the density and size of the disks and the placement of the EPSL with respect to the signal line. Our results showed that only a few rows of EPSL structures need to be placed under the transmission line. This is favorable, since it allows tightly spaced lines.

A second type of transmission line, coupled microstrip lines, was then considered. Tightly spaced microstrip lines are common in T/R module packages and other high density circuit packages. The work involved creating a method to reduce the insertion loss and reduce coupling between two microstrips that are placed very closely to one another. Of special interest was the performance at millimeter wave frequencies that range from (30GHz to 67 GHz). The results show that the EPSL reduces loss, reduces coupling between adjacent lines, and modifies the effective permittivity in microstrip. The largest effect happens on the high permittivity materials and when the embedded pattern layer is close to the signal conductor. to see the largest performance improvement. The apparent permittivity of transmission lines that use the embedded patterned layer is larger than those without the patterned layer. This has the effect of lowering the characteristic impedance of the microstrips while maintaining narrow conductor widths.

An equivalent transmission line model that involves the per-unit-length RLCG parameters was generated. This model provides additional insight at how the transmission line with the EPSL performs over frequency. Computer models with transmission lines are much faster to run that full-wave EM models. Transmission line models also help us identify the particular contributors to loss, coupling, group delay, etc.

The final step of the research compared how the presence of the EPSL helps millimeter wave packaging. The EPSL requires the fabrication and bonding of another vertical layer in a package. This is only interesting if there is a substantial performance benefit, or it allows miniaturization and tighter spacing in a module. The results show that the coupling between microstrips with the EPSL is very low. Coupled microstrip lines without and EPSL must be placed at least twice as far apart from another to experience the equivalent level of isolation. This is a benefit as the EPSL does indeed allow tighter line spacing with good isolation performance.

Near term work will consider aperiodic patterning of the embedded patterned layer as an impedance control technique and the characterization of other element shapes for the embedded patterned layer.

III. Additional Research Details

Additional details of two areas: the characterization of surface roughness on transmission lines and the characterization of tightly coupled microstrip interconnects are provided.

a. Surface Roughness on CB-CPW (without EPSLS)

The geometric dimensions of transmission line interconnects are shrinking as engineers design smaller and faster systems by moving into the high frequency regime. Transmission lines operating at high frequencies see an increase in resistive losses that can adversely affect the performance of the electrical system. For smooth conductors, the series resistance increase with frequency is attributed to the skin depth, which is inversely proportional to the square root of frequency. In practice, the conductor surfaces are roughened by the manufacturers to promote adhesion between the dielectric and conductors in printed circuit boards (PCBs). In this work, a method to simulate the effects of conductor surface roughness on conductor-backed coplanar waveguide (CB-CPW) interconnects using 3-D full wave simulation tools was created. The high-frequency structure simulator (HFSS) from ANSYS was implemented for rough surfaces with Gaussian correlation functions. This type of function is consistent with published results that included extensive evaluation of actual circuit boards from various manufacturers. The rough surfaces that exist between the dielectric and copper foils are modeled using a statistical random process approach. The varying heights for the random rough surface with specified autocorrelation function (ACF), root mean square height (Hrms), and correlation length (λ) are generated using Matlab. This parameterization is similar to the analysis of EM scattering from rough ocean waves. The statistical parameters were used in HFSS to model and simulate the performance of the CB-CPW interconnect with rough conductor surfaces. The results show that both Hrms and λ influence the overall attenuation coefficient, and the trends are consistent with the other studies in this area. The method created provides designers with a technique to characterize the effect of conductor surface roughness for different types of transmission lines with varying substrates and extent of conductor roughness.

Fig. 1 shows an example of a signal conductor with and without roughened surfaces. Fig. 2 shows the attenuation coefficient and the insertion loss for a CB-CPW line with slightly roughened conductor surfaces. Surfaces with a larger Hrms indicate a greater amount of surface roughness.   These results show that rough surfaces can affect overall attenuation. While the results do not show a huge effect for longer lines, there may be instances at higher frequencies where control of surface roughness may be important. The results also show that the effects of surface roughness have an impact at millimeter wave frequencies.

This is because the overall rough structures on the conductors are very small with respect to wavelength at lower frequencies of operation. The method created can be used to provide a realistic estimate when conductor surface roughness is implemented for lines with EPSLs.

Insertion Loss and Coupling of Tightly Spaced Microstrip Lines with EPSLs

The EPSL consists of a patterned layer of elements. Realization of the EPSL involves printed, flat, sub-wavelength conductors placed between the ground and signal layers of a RF transmission line. The EPSL pattern in this work are flat disks.

To investigate the effect of the EPSL a structure consisting of two tightly spaced adjacent microstrips is modeled. Alumina with a nominal dielectric with εr=10, tan δ=0.002 and a substrate height h=4mil was used. The thin substrate and closely spaced microstrips create a challenging microwave interconnect.problem. The microstrips have width w=6mil with a spacing s1=4.5mil and have a ground plane at the bottom surface of the substrate. A conductor thickness of 0.7mil is included to model lossy copper conductors with a conductivity σc=5.8x107 S/m. The substrate width and length is 200mil long while the microstrips span the entire length. When adding the EPSL to the nominal model, disks were chosen with the following dimensions: diameter d=6.5mil, spacing s2=4.5mil and thickness t=0.35mil. Fig. 3 illustrates the interconnect structure and dimensions.

The EPSL consists of 3 columns and 15 rows of disks that are placed between the top conductors and the bottom ground plane. The z-position, zpos, between the top and bottom conductors was varied to characterize the impact of the placement of the EPSL performance of this structure. All of the coupling and insertion loss results are renormalized to Zo, which is the characteristic impedance of a single ended microstrip without an EPSL. Fig. 4 shows the insertion loss and return loss of the cases with and without the EPS and shows how the height of the EPSL impacts the results. The results show that the best results occur when the EPSL is very close to the microstrip signal line. The insertion loss at 65 GHz is reduced by 4dB when the EPSL is included. While S11 is slightly increased, this is because the EPSL also modifies the relative permittivity and thus the Zo of the line is now mismatched from the microstrip without an EPSL.

The diameter of the disks are λ/33 at 30GHz and λ/20 at 60GHz. The EPSL has almost no impact on the performance of the microstrip line at frequencies below 33GHz, as the disks are just too electrically small to impact the signal propagation. The coupling to ports 3 and 4 are also impacted by the presence of the EPSL. The S14 coupling is reduced by 4dB, while the coupling to port 3 is slightly higher and increases from -60dB for the case without the EPSL to -30dB for the case when the EPSL very close to the signal line.

The changes in Zo, with the EPSL indicated that the effective permittivity is changed from the nominal case when the EPSL is present. This is a promising result, as it should allow a transmission line with a Zo that varies with x to be created by varying the disk geometry. To investigate this shift, the effective permittivity of a single ended microstrip line with and without the EPSL was calculated. The effective permittivity, εeff was extracted using the extracted group delay GD and the physical length of microstrip line. Fig. 5 shows how effective permittivity for coupled lines with and without the EPSL for Almunia (εr=10) and Megron 6 (εr=3.5).The EPSL increases the relative permitivity which allows for additional circuit miniaturization and additional design options for integration with very small on-chip transmission lines.

The per-unit-length RLCG parameters for the coupled microstrips with and without the EPSL were extracted. These parameters are useful for creating a transmission line model of a uniform structure. The RLCG parameters are computed from the complex propagation coefficient obtained from S21 where S21= e-■l, when the ports are match terminated. The results show that when the EPSL is included, R and G are reduced by half and L and C are nearly doubled over the values of coupled microstrip lines without the EPSL. This would account for the reduction in insertion loss, yet more research is needed to understand how the higher L and C values reduce S14 coupling.

One final analysis that was conducted was to compare how well coupled lines with the EPSL perform to coupled lines without an EPSL. First the coupling and return loss of coupled microstrip lines with a line spacing (s1) of 4.5 mils with an EPSL were quantified. Then an equivalent-length microstrip line without an EPSL was created. In order to match the performance of the coupled lines with an EPSL, the spacing between coupled microstrip lines had to be increased to 9 mils. Fig. 6 shows the results. These results show that the presence of the EPSL does indeed allow tighter line pitches which allows for more options for chip-to-package integration.

Technology Transfer

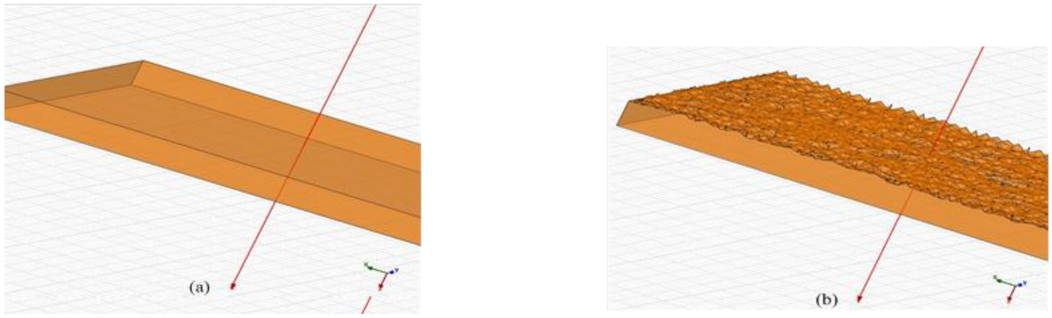


Fig. 1. Signal conductor with (a) smooth surface; (b) randomly roughened surface. Only the surface of the conductor making contact with the substrate is roughened.

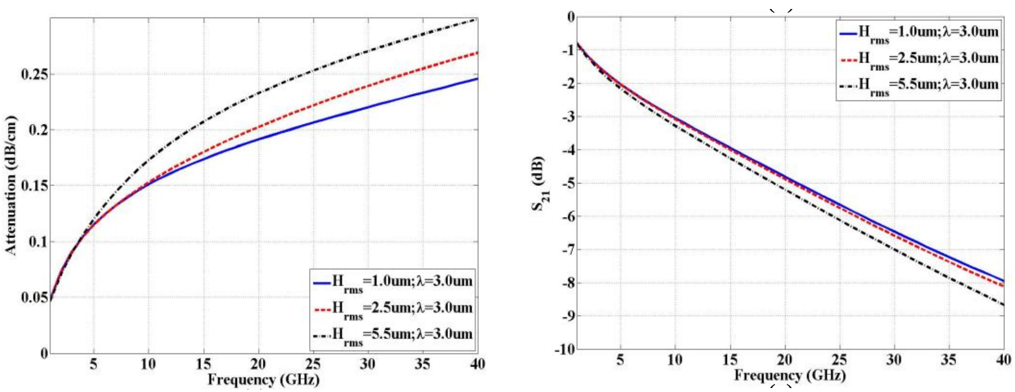
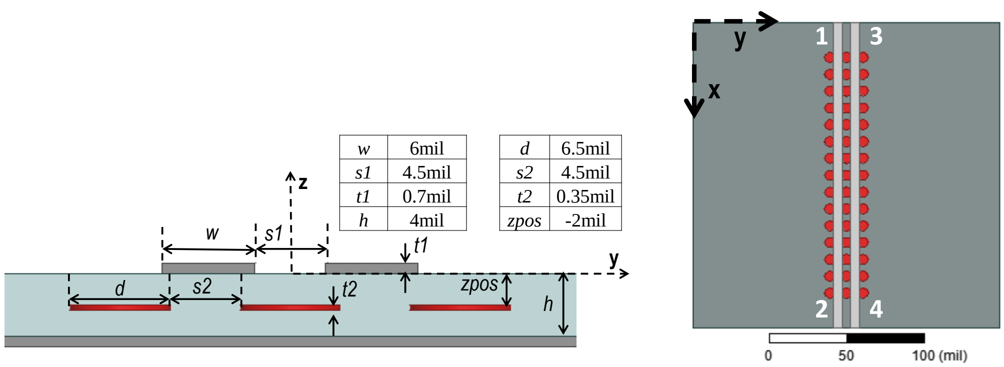


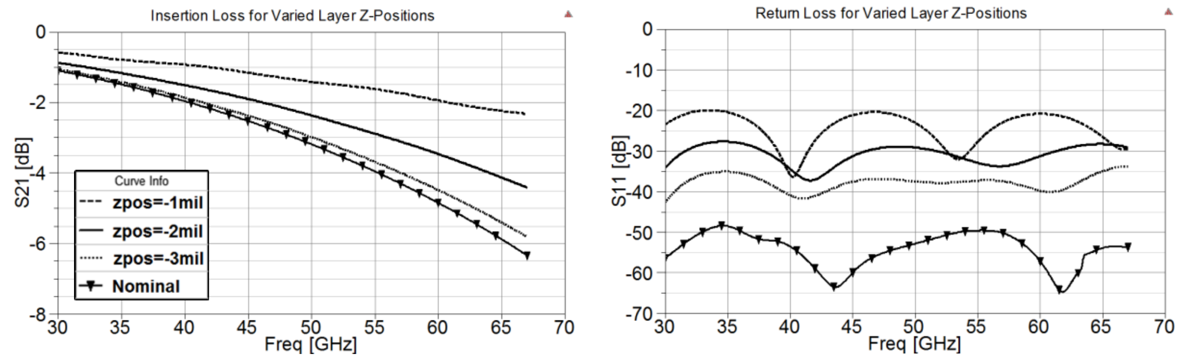
Fig. 2. (a) Attenuation coefficient per unit length; (b) insertion loss as a function of frequency for constant λ (3.0 μm) and varying H_rms (1.0 μm, 2.5 μm and 5.5 μm) for a 7 inch long CB-CPW.



w	6mil
s1	4.5mil
t1	0.7mil
h	4mil

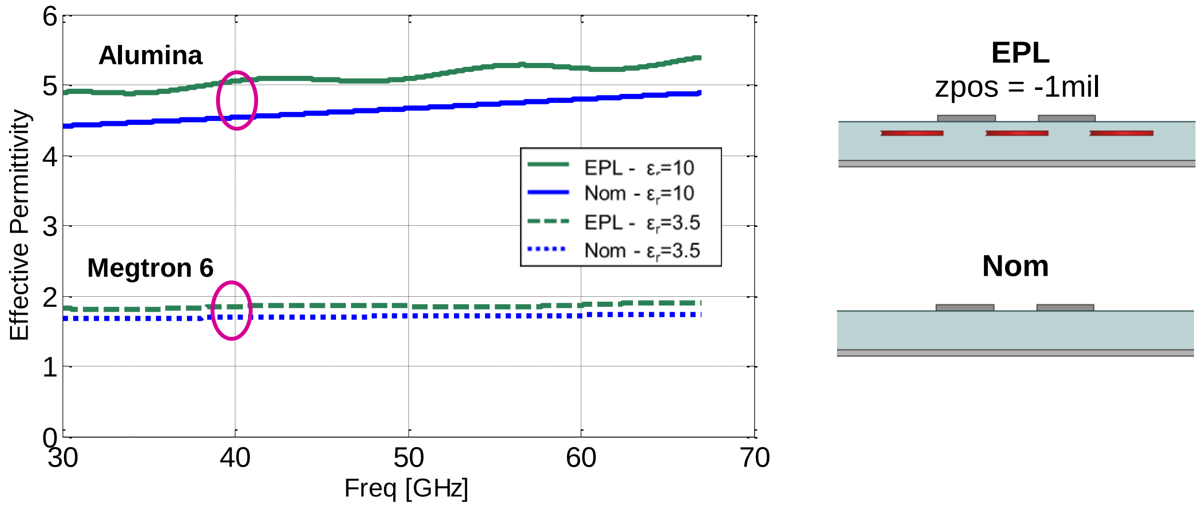
d	6.5mil
s2	4.5mil
t2	0.35mil
zpos	-2mil

Fig. 3. (a) Cross section of the tightly coupled microstrips with the embedded patterned layer accompanied with tabled dimensions. (b) Top down view of the full model with port number assignments.



(a) (b)

Fig. 4. (a) insertion loss S_{21} and (b) return loss S_{11} adjacent microstrips with EPSL



$$\varepsilon_{eff} = \frac{c * GD}{l_{phys}} \qquad \text{w/} \qquad GD = \frac{1}{360°}\frac{d\varphi}{df}$$

Fig. 5 Change in Effective Permittivity with the EPSL Layer. Formulas show how effective permittivity is computed from group delay.

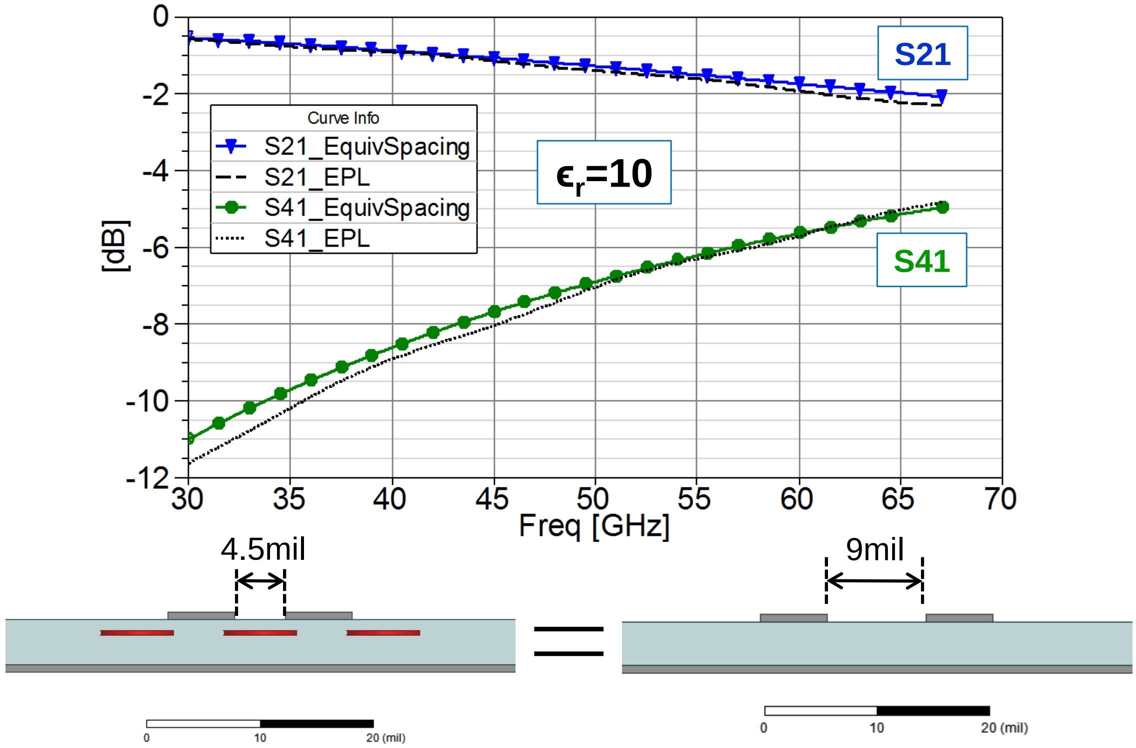


Fig. 6 Performance of tightly coupled microstrip lines with an EPSL to coupled microstrip lines without an EPSL.